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BODNER-PARTOM VISCOPLASTIC MODEL IN STEALTH FINITE DIFFERENCE CODE

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Most of the state-of-the-art finite difference codes are still incapable of describing strain-rate and loading history dependent plastic flow behaviors in metals. The main objective of our work was to develop a computational algorithm for describing viscoplastic constitutive model in a finite difference code. A subincremental time stepping, iterative numerical scheme was used to describe Bodner-Partom viscoplastic model in the STEALTH finite difference code. Several special purpose subroutines were developed and incorporated into the code. The new routines were validated by comparing the solutions obtained for several model problems with the already available solutions of those problems. This report also describes in detail the input preparations for the Bodner-Partom model and the flowcharts associated with the numerical algorithms.

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11. (continued)

STEALTH Finite Difference Code

SUMMARY

The objective was to develop an algorithm for describing elastic-viscoplastic constitutive equations based on the Bodner-Partom model in the STEALTH finite difference code. To ensure convergence of the B-P solutions, several parameters (TOLRSD, RLAXSD, MITRSD, MCUTSD, and TCFSD) were introduced into the algorithm. Based on the results of various test cases, the algorithm seems to work efficiently using the default values of these parameters. However, when convergence problems arise, the user can adjust the values accordingly.

The validity of the newly developed routines (described in Appendix A) were checked through two different methods. In the first method, a dynamic tensile test under uniaxial stress state was simulated using STEALTH. The stress-strain responses at various strain rates were successfully compared with the direct solutions of the Bodner-Partom equations under uniaxial stress state. In the second approach, for a rate-independent elastic-perfectly plastic material, a plate impact test simulation was carried out using (1) the regular material model that is available in STEALTH, and (2) the developed Bodner-Partom model. The results in terms of velocity and stress history in the target compared extremely well.

We have used quite successfully the Bodner-Partom model option that has been described in this report to characterize various metals. We can describe rate dependent, rate-independent, and strain hardening material behaviors using STEALTH with the new material option; the corresponding results for different steel, aluminum and copper are given in Reference 10. The development and the demonstrated use of a sophisticated strain-rate and history dependent material model in a finite difference code will certainly encourage many code users who work in armor design to employ such a model in the computer simulation of high velocity impact problems.

PREFACE

This work was conducted under contract No. F33615-82-C-5126 for AFWAL/MLLN. The contract monitor was Dr. Theodore Nicholas. His many helpful comments during the execution of the program were greatly appreciated. Mr. William Cook (AFATL/DLJW) has supplied partial funding for this project. His interests and encouragements were also appreciated.

This project was carried out at the University of Dayton Research Institute by Dr. A. M. Rajendran and D. J. Grove of the Structural Integrity Division. This report covers the time period of April 1985 through April 1986.

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SECTION 1
INTRODUCTION

Several applications of structural materials involve impact type loading. Under such loading conditions, the material experiences high rates of strain, large deformation, high pressures and high temperatures. The dynamic materials characterization becomes very important in the analysis of weapon effects, including structural response to explosive loading. Within the last decade, the development of finite element/difference codes has provided additional analytical capability in understanding these problems. It is now well established (see Reference 1) that the material descriptions can significantly affect the computational results. Code users have often been unable to apply sophisticated constitutive relations for describing materials. For example, most computer codes still do not account for the strain-rate and pressure dependence of yield and flow stresses.

Several constitutive theories based on state variables have been developed by various investigators (References 2 thru 6). One of the advantages of state variable theories is that changes in constitutive behavior with load history can be modelled by suitably modifying the evolution equation of the corresponding state variable. Depending on the complexities of the loading, more than one state variable may be introduced into the theory.

The objective of the present work is to develop algorithms (computer subroutines) describing rate-dependent (viscoplastic) constitutive equations for a general purpose finite difference code. For this purpose, a state-of-the-art finite difference code called 'STEALTH' (see Reference 7) was selected.

The state variable based viscoplastic theory developed by Bodner and Partom (see Reference 2) was chosen in the present work for three reasons: (1) ability to predict the response of material to a broad range of load histories, (2) adaptability to finite difference analyses of structural components, and (3) ease with

which the parameters in a constitutive model can be determined from high strain-rate experiments.

The Bodner-Partom model is described in Section 2. The yield models in STEALTH and the new B-P model algorithms are briefly discussed in Section 3. The validation of the developed routines is discussed in Section 4. Finally, Appendix A discusses the additions required to include the Bodner-Partom model in STEALTH, while Appendices B, C, and D supply additional details concerning the input preparations, new subroutines, and flow-charts. To understand the modifications, it is essential that one is familiar with the STEALTH code structure. We have strictly followed the STEALTH-code conventions in the input preparations. Since the STEALTH manual (Reference 7) describes in detail the conventions that have been employed in its preparations, we have described only the additions that are needed to use the Bodner-Partom model. The iterative solution scheme that has been used in the Bodner-Partom model routines, in general, can be understood by any code developer/user from the self-explanatory flowcharts in Appendix D.

SECTION 2

BODNER-PARTOM MODEL

For assumed small strains, the total strain rate is taken to be decomposable into elastic (reversible) and inelastic (nonreversible) components

$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}^{e}_{ij} + \dot{\varepsilon}^{p}_{ij} \tag{1}$$

which are both nonzero for all loading/unloading conditions. The elastic strain rate, $\dot{\varepsilon}^{e}_{ij}$, is related to the stress rate by the time derivative of Hooke's Law (based on the assumption of small strains). The inelastic strain rate $\dot{\varepsilon}^{p}_{ij}$ can be expressed in the general form

$$\dot{\varepsilon}^{p}_{ij} = \dot{\varepsilon}^{p}_{ij}(\sigma_{ij}, Z_k, T) \tag{2}$$

where Z_k are one or more internal (inelastic) state variables and T is the temperature. In particular, $\dot{\varepsilon}^{p}_{ij}$ is taken to follow the Prandtl-Reuss flow law of classical plasticity, (assuming incompressibility):

$$\dot{\varepsilon}^{p}_{ij} = \dot{e}^{p}_{ij} = \lambda S_{ij} \tag{3}$$

where $\dot{e}^{p}_{ij}$ and S_{ij} are the deviatoric plastic strain rate and the stress, respectively. Squaring equation 3 gives

$$1/2\ \dot{e}^{p}_{ij}\ \dot{e}^{p}_{ij} = D^{p}_{2} = 1/2\lambda^{2} S_{ij}\ S_{ij} = \lambda^{2} J_{2}$$

or

$$D^{p}_{2} = \lambda^{2} J_{2} \tag{4}$$

where D^{p}_{2} is the second invariant of the plastic strain rate and J_2 is the second invariant of the stress deviator.

The basic assumption of the formulation is that all inelastic deformations are governed by a continuous relation between D_2^p and J_2. The particular form that was established to describe this relation was based on the concepts and equations of "dislocation dynamics" and it is given by:

$$D_2^p = D_o^2 \{\exp[(-\frac{Z^2}{3J_2})^n \frac{(n+1)}{n}]\} \qquad (5)$$

where D_o is the limiting value of the plastic strain rate in shear. n is a material constant that controls strain rate sensitivity and also influences the overall level of the stress-strain curves. It is a fundamental constant and it is not dependent on the loading history. Z is the inelastic state variable which represents the measure of the overall resistance to plastic flow caused by microstructural barriers that impede dislocation motion. Combining equations 3 through 5, the plastic strain rate takes the form

$$\dot{\varepsilon}^p_{ij} = D_o \exp \{-(\frac{Z^2}{3J_2})^n \frac{(n+1)}{2n}\} \frac{S_{ij}}{\sqrt{J_2}} \qquad (6)$$

The general form for the evolution equations, i.e., history dependence, of the inelastic state variable Z is,

$$\dot{Z} = F(J_2, Z, T) \qquad (7)$$

For conditions of uniaxial stress of constant sign, the hardened state with respect to plastic flow is assumed to be represented by a single state variable Z which depends on plastic work. This corresponds to isotropic hardening and the evolution equations employed can be shown to be in the form of equation 7. The corresponding form is then based on the concept that plastic work, W_p, controls the hardening process, and that the plastic work and its time derivative are functions of σ_{ij} and $\dot{\varepsilon}_{ij}$. The

evolution equation for the state variable is assumed to have the form:

$$\dot{Z} = m(Z_1 - Z)\ \dot{W}_p \tag{8}$$

where, $\dot{W}_p = \sigma_{ij}\ \dot{\varepsilon}^p_{ij}$. The above equation can be integrated with m and Z, as material constants. The relation between Z and W_p becomes,

$$Z = Z_1 - (Z_1 - Z_o)\ e^{-mW_p} \tag{9}$$

Z_o is the initial value of Z corresponding to the reference state from which W_p is measured. It is noted that Z_o could take any value between 0 and Z_1. The initial yield stress of the uniaxial stress-strain relation would be directly influenced by Z_o. Z_1 corresponds to the saturation state of Z at which the material reaches a nonwork hardened condition. m is a material constant that controls the rate of work hardening.

For materials which exhibit strong strain hardening, m was made a function of W_p by Bodner and Merzer (Reference 9). The expression for m was:

$$m = m_o + m_1\ e^{-\alpha W_p} \tag{10}$$

which adds two more constants. When m is defined by equation 10, the relationship (equation 9) is not valid. The expressions for Z when integrated after replacing m by the definition (equation 10), yields the following relationship between Z and W_p:

$$Z = Z_1 - (Z_1 - Z_o)\ e^{-m_o W_p}\ e^{-\frac{(m_o + m_1 - m)}{\alpha}} \tag{11}$$

The plastic strain rate expression, (equation 6) $\dot{\varepsilon}^p_{ij}$, corresponding to uniaxial stress state ($\sigma_X \neq 0$, $\sigma_Y = \sigma_Z = 0$), becomes

$$\dot{\varepsilon}^p = \frac{2}{\sqrt{3}} D_o \exp \left\{ - \left(\frac{n+1}{2n}\right) \left(\frac{Z}{\sigma}\right)^{2n} \right\} \tag{12}$$

The expression for the state variable, Z, becomes

$$Z = Z_1 - (Z_1 - Z_o)\, e^{-mW_p} \tag{13}$$

For a given stress or strain rate history under uniaxial stress state, the calculation of stress/strain response is fairly straight forward through a first order Euler's integration scheme of equations (12) and (13).

In general, the stress/strain response under a multiaxial stress state requires the solution of the second order tensor $\dot{\varepsilon}^p_{ij}$ as expressed by the equation (6). The algorithm developed for the STEALTH code is for three dimensional states of stress. The essential changes that were introduced in the regular STEALTH routines are discussed in detail in Appendices A through D. The following section discusses the results obtained from STEALTH for the validation of B-P model algorithms.

SECTION 3
INCORPORATION OF B-P MODEL ALGORITHM

The elastic-plastic constitutive model in the standard STEALTH version is not capable of describing time dependent material response. The description of the yield model in STEALTH is fairly straight forward. In this section, we briefly discuss the algorithm that is available in STEALTH to describe rate independent elastic-plastic material response. The B-P model algorithm to describe strain rate and history dependent material response is also discussed.

3.1 YIELD MODELS IN STEALTH

Several yield models in which the flow stress is function of pressure, internal energy, and distorsional energy are available in STEALTH. Those models are in general empirical and they can not describe the strain rate and loading history dependent yield and flow stresses. The simplest model that is available to calculate the flow stresses which do not depend on pressure is the elastic-perfectly plastic material model. The model is given by,

$$3J_2 = Y^2$$

where Y is the constant yield stress. Y is the only material parameter that is needed to describe the model.

In STEALTH, the stress deviators, S_{ij} are estimated based on the elastic material behavior at the end of each time step. The effective stress, σ_{eff} is estimated from the following relationship:

$$\sigma_{eff} = \sqrt{3J_2} = \sqrt{\frac{3}{2} S_{ij} S_{ij}} \ .$$

σ_{eff} is then compared with the yield stress (Y). When σ_{eff} is greater than Y, the plastic flow is assumed to occur. The values of the estimated S_{ij}^{est} are multiplied by a correction factor (β) so

that the S_{ij} lie on the Von-Mises yield surface. The corresponding expression is given by,

$$\frac{3}{2}\,(\beta S_{ij}^{est})\,(\beta S_{ij}^{est}) = Y^2$$

β can be calculated as:

$$\beta = \sqrt{\frac{2Y^2}{3\ S_{ij}^{est}\ S_{ij}^{est}}}$$

The stress deviator S_{ij} corresponding to the plastic flow is then given by,

$$S_{ij} = \beta S_{ij}^{est} .$$

When there is no plastic flow, i.e., $\sigma_{eff}<Y$, β is equal to 1. The important assumption in the above algorithm is that the stress deviators do not depend on the loading rate, time or history. As mentioned earlier, when the material behavior is viscoplastic, these kinds of yield models are no longer valid. In fact, most of the metals exhibit rate dependency under very high strain rates. The calculations of S_{ij} will require an iterative scheme. Since the B-P model is a viscoplastic model, we developed an algorithm in which the stress deviators are computed through a subincremental time stepping scheme as described in the following section.

3.2 BODNER-PARTOM MODEL IN STEALTH

We described the B-P model earlier in detail (Section 2). The B-P model is simply given by the following two relationships:

$$\dot{\varepsilon}^{p}_{ij} = D_o\, e^{-\left(\frac{n+1}{2n}\right)\left(\frac{Z^2}{3J_2}\right)^n} \frac{S_{ij}}{\sqrt{J_2}} \qquad (14)$$

and

$$\dot{Z} = m(Z_1 - Z)\dot{W}_p \tag{15}$$

A subincremental time stepping scheme is used to calculate the deviatoric stresses, S_{ij} for each finite difference time step. The global time step, Δt, is further divided into small steps in a special purpose subroutine to describe the B-P model. At the end of each global time step, STEALTH provides the total strain rates, $\dot{\varepsilon}_{ij}$, the volumetric strain rate, $\dot{e}$, and the pressure, P; S_{ij}, σ_{ij}, and $\dot{\varepsilon}^p_{ij}$ are unknown.

In the current numerical scheme, the plastic strain rates are estimated for each subincremental time step using equations 14 and 15 with the value for J_2 calculated from the known S_{ij} values at the beginning of the step. The elastic strain rates, $\dot{\varepsilon}^e_{ij}$, are estimated from the estimated $\dot{\varepsilon}^p_{ij}$ and the known total strain rates, $\dot{\varepsilon}_{ij}$. The new estimates for $\dot{S}_{ij}$ can be made from the following relationship:

$$\dot{S}_{ij} = \dot{\sigma}_{ij} + \dot{p}\delta_{ij} \tag{16}$$

where

$$\dot{\sigma}_{ij} = E_{il}\dot{\varepsilon}^e_{lj} \tag{17}$$

and

E_{il} are the elements of the elastic modulus matrix.

Using the new estimates for $\dot{S}_{ij}$, the improved values for the plastic strain rates at the end of the subincremental time step can be computed. This procedure is continued until the values of $\dot{S}_{ij}$ computed for the two successive iterations converge to the same values within the tolerant limits.

The algorithm has been designed to handle convergence problems. If any one component of the stress deviators, S_{ij}, does not converge within the imposed iteration limit and convergence tolerance, the subincremental time step is reduced. The solution procedure for the current time interval is repeated using this smaller time step. If the S_{ij} still fail to converge after the maximum allowable number of time step reductions, the program creates a debug output file for further diagnosis and stops execution.

The user can also control several other parameters in the convergence of the Bodner-Partom solution. A relaxation factor, R (RLAXSD)*, is used to weigh the previous S_{ij} estimates with the current S_{ij} in order to obtain improved values for the next iteration, as follows:

$$S_{ij}^{est} = R \cdot S_{ij} + (1-R) \cdot S_{ij}^{est} \qquad (18)$$

When R=1, the new estimates are equal to the current values and when R=0.5, the new estimates are simply the averages of the previous estimates and the new values. Generally, R=1 works well; sometimes, however, R must be reduced (to 0.75 or 0.5) in order to prevent an oscillating solution. Another parameter which affects convergence is $\Delta\varepsilon_{max}$(DEMAX)*, the maximum allowable change in the total strain during a subincremental time step. A reduction in $\Delta\varepsilon_{max}$ can result in a smaller initial subincremental time step, which should help the S_{ij} converge more rapidly. We can also adjust the relative convergence tolerance (TOLRSD)* to help achieve convergence. Likewise, an increase in the maximum number of iterations (MITRSD)* allowed may sometimes give the solution a better chance of converging. Finally, a decrease in the subincremental time step size may aid in the convergence of the S_{ij}; this can be accomplished by increasing either the maximum number of time step reductions (MCUTSD)* or the time step reduction factor (TCFSD)*. These various convergence related

* See Appendix C

parameters are described in Appendix C as input parameters. We found that several test problems converged consistently using the default values of these parameters. A user may use the default values unless convergence problems are encountered.

To incorporate the B-P model into STEALTH, we developed several subroutines. A series of flowcharts, given in Appendix D, describes the steps involved in the numerical scheme. The following section focuses on the model problems which were considered for the validation of the developed numerical scheme.

SECTION 4
VALIDATION OF THE ALGORITHM

The new subroutines that describe the Bodner-Partom constitutive equations must be checked for their validity. For this purpose, two approaches were considered. In the first (direct) approach, the stress-strain response of a uniaxial tensile bar was computed from STEALTH using the new routines. The results were compared with the solution obtained from an independent program (BPSOLVE) which solves the uniaxial Bodner-Partom equations (12) and (13) using Euler forward integration scheme. The second approach is an indirect way of checking the validity through a plate-impact test simulation (see Reference 8). In this section, these two approaches are discussed in detail.

4.1 DIRECT APPROACH

A thin cylindrical bar being pulled in tension at a constant velocity, as shown in Figure 1, was considered. The bar was modeled using the 'THIN OPTION' that is available in STEALTH (see Reference 7). This option provides solutions to problems in which the stress state is one-dimensional as in the uniaxial tensile test. In the finite difference analysis, the bar was modeled with 10 zones.

We considered two different material behaviors: (1) rate independent, elastic-perfectly plastic solid, and (2) rate dependent, elastic-viscoplastic, strain hardening solid. The B-P model parameters used in the first case were:

$$D_o = 10^8/\text{sec}$$
$$Z_o = 15 \text{ kbar}$$
$$Z_1 = 15 \text{ kbar}$$
$$m = 0.2 \text{ kbar}^{-1}$$
$$n = 6.5$$

Typically a large value of n indicates that the material is rate independent. The same initial and saturation values of Z_1 indicate that the material is perfectly plastic. In this

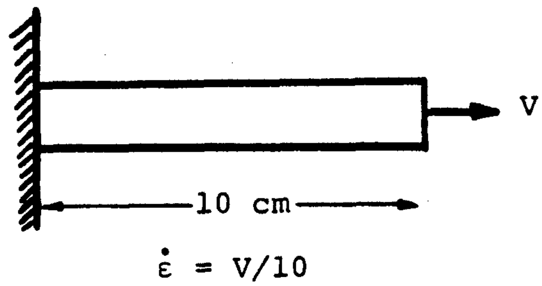

Figure 1. A Long Cylindrical Bar under Uniaxial Stress Condition. V is the Constant Pull Velocity.

particular case, the strain hardening parameter m cannot influence the material response and it becomes a redundant parameter. However, an arbitrary value of 0.2 was used for m in the simulation. Using the Bodner-Partom model algorithm in STEALTH, the stress response in the tensile bar was computed. The corresponding input data for the STEALTH run is given in Appendix E. The pull velocity in the run was assumed to be 10 m/sec. The average strain rate in the bar corresponding to this velocity is 100/sec. This average strain rate is typically experienced by zone 5 which is the middle zone. The stress-strain curve obtained from BPSOLVE for a strain rate of 100/s compared extremely well with the STEALTH results as can be seen from Figure 2. We also calculated stress-strain curves for strain rates 1000 and 10,000s^{-1}. The curves were essentially the same as in Figure 2. This validates the solution algorithm since the material was modeled as a rate independent solid.

We repeated the simulation of the uniaxial tensile bar test modeling the material as a rate dependent, strain hardening, elastic-viscoplastic solid. The model parameters we chose for this case were:

$$
\begin{aligned}
D_o &= 10^8/\text{sec} \\
Z_o &= 55 \text{ kbar} \\
Z_1 &= 70 \text{ kbar} \\
m &= 1.5 \text{ kbar}^{-1} \\
n &= 0.4
\end{aligned}
$$

A relatively low value of n indicates the response is significantly rate dependent. The strain hardening behavior is represented by the different values for Z_o and Z_1, and a value of 1.5 for m. The cylindrical bar problem was simulated using STEALTH with these B-P model parameters. Three different runs were made with pull velocities of 10, 100, and 1000 m/sec. The corresponding average strain rates in the bar were 10^2, 10^3, and 10^4/sec. Using BPSOLVE the stress-strain responses for these strain rates were obtained and were compared with the STEALTH

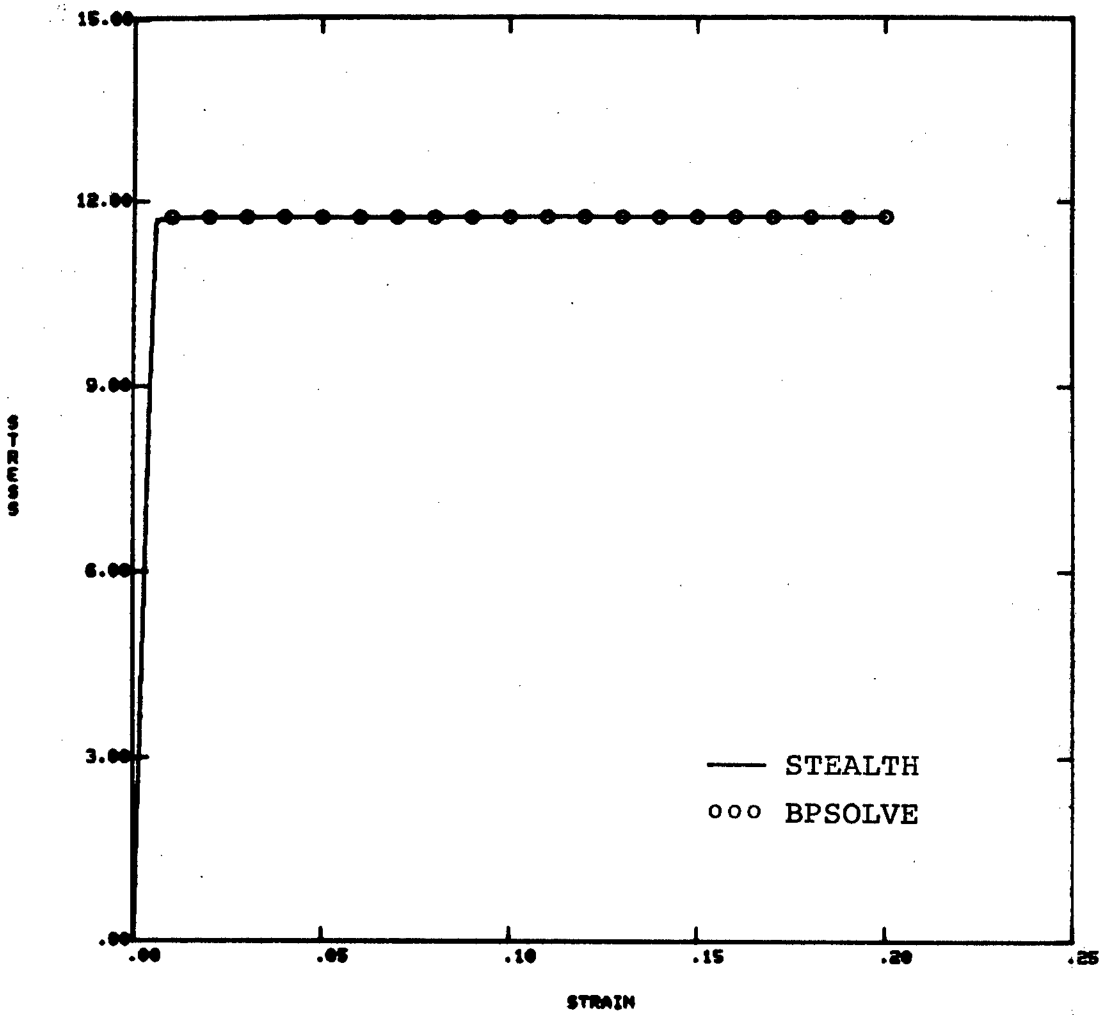

Figure 2. Comparison of Stress-Strain Curves Obtained from STEALTH Using B-P Routines and BPSOLVE at a Strain Rate of 100 s^{-1} for Rate-Independent Material Behavior.

results as shown in Figure 3. It can be seen that the STEALTH solutions [solid line] compared extremely well with the direct solutions [symbols] of the B-P equations.

4.2 INDIRECT APPROACH

The idea behind this approach was to compare the stress/velocity history of the target plate obtained from a conventional plate-impact test simulation (see Reference 8 for details) using two constitutive models: (1) the rate-independent elastic-perfectly plastic material model that is already available in STEALTH, and (2) the Bodner-Partom model that is included in STEALTH as a special purpose material model. The rate independent elastic-perfectly plastic model used in the first simulation was modeled by Bodner-Partom equations and the corresponding B-P model constants were used in a second simulation of the same problem. Since the material behavior used in both simulations is essentially the same, the velocity and stress history of the target calculated from the STEALTH with and without the B-P model should be the same. This indirect approach was used, and results were obtained for an impact velocity of 300 m/sec. The input data used in STEALTH is given in Appendix F.

The B-P model constants corresponding to the rate-independent elastic-perfectly plastic materials were,

$$\begin{aligned} Z_o &= 15.0 \text{ kbar} \\ Z_1 &= 15.0 \text{ kbar} \\ m &= 0.2 \text{ kbar}^{-1} \\ n &= 6.5 \\ D_o &= 10^8/\text{sec} \end{aligned}$$

The uniaxial stress-strain curve that is described by the B-P model using these constants is shown in Figure 4. The flow stress, Y_o, in the figure was employed in the regular STEALTH run (without B-P model routines) and the corresponding value was Y_o = 11.8 kbar.

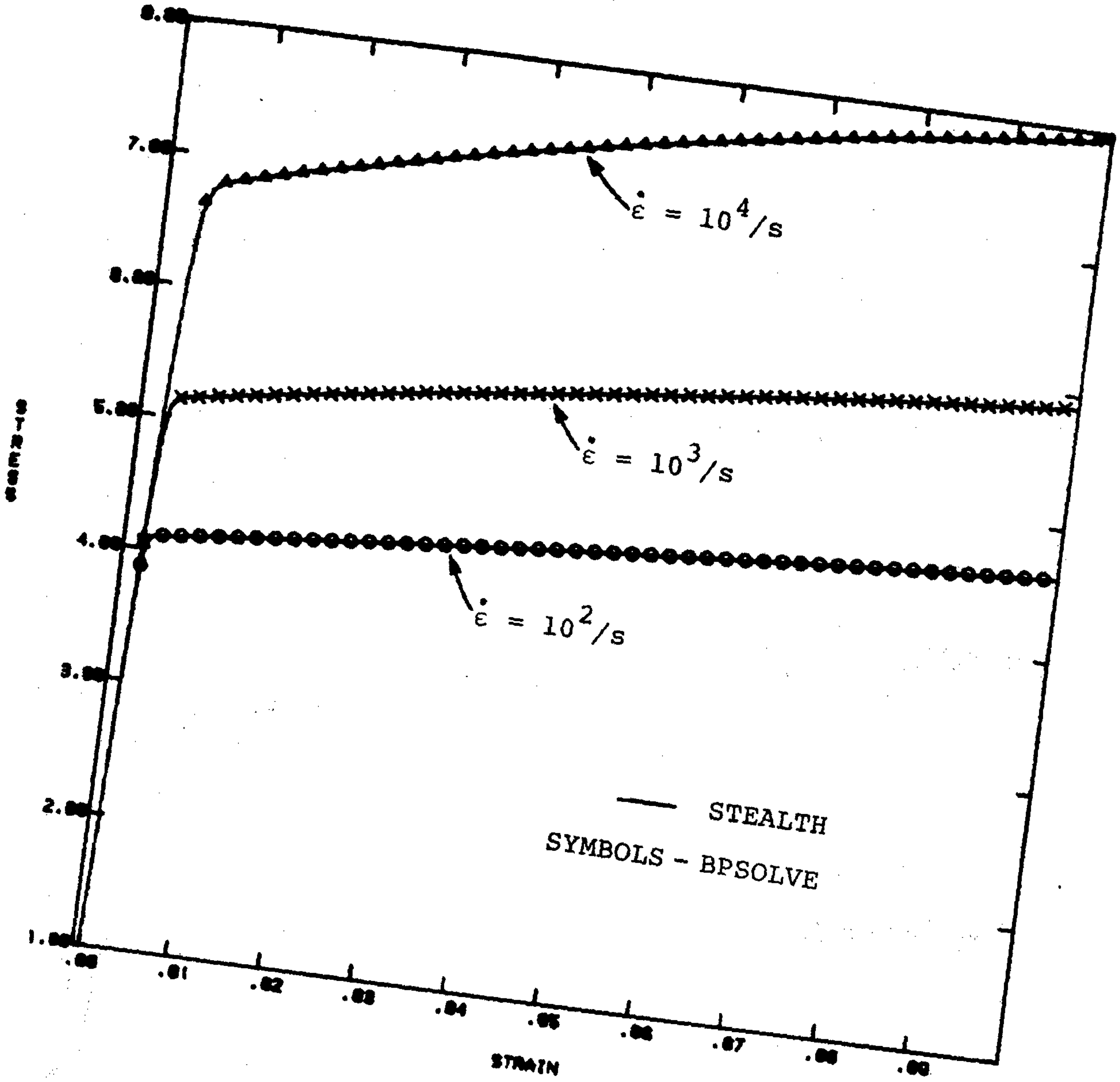

Figure 3. Comparison of Stress-Strain Curves Obtained from STEALTH Using B-P Routines and BPSOLVE at Various Strain Rates for Rate Dependent Material Behavior.

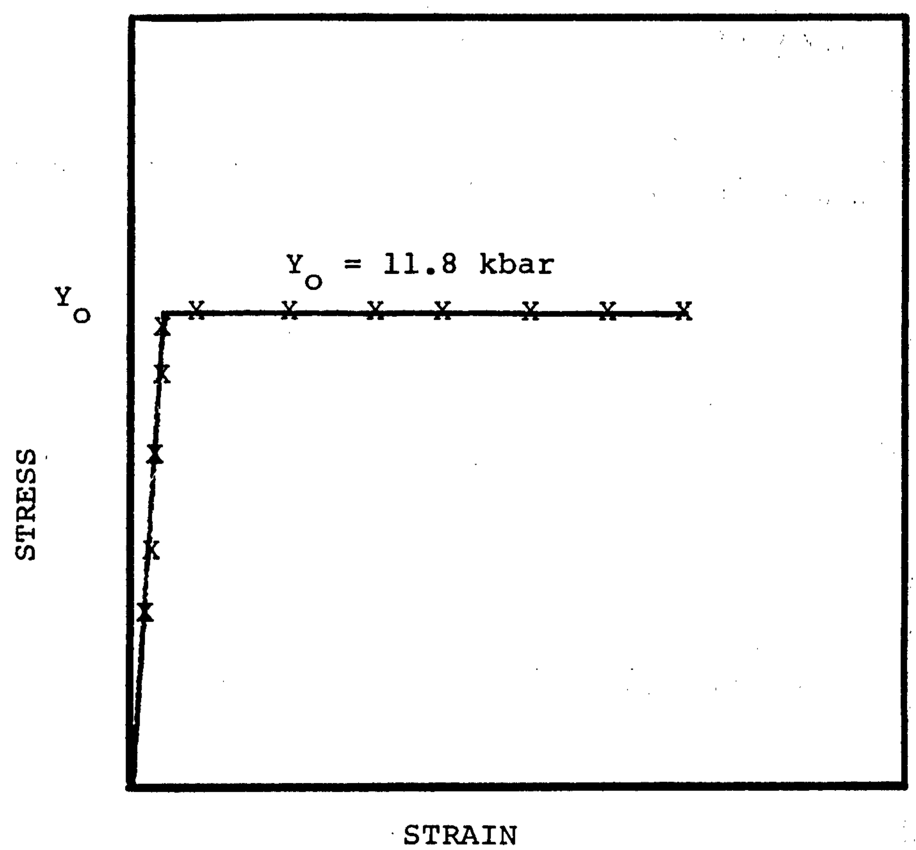

Figure 4. The Elastic-Perfectly Plastic Stress-Strain Curve [— Solid Line] and B-P Simulation [Symbol] used in STEALTH Simulations of Plate Impact Tests.

As can be seen from Figures 5 and 6, the free surface velocity of the target and the stress history at the spall plane obtained from the two cases are almost identical. This further validates the newly developed subroutines that describe the Bodner-Partom constitutive equations in STEALTH.

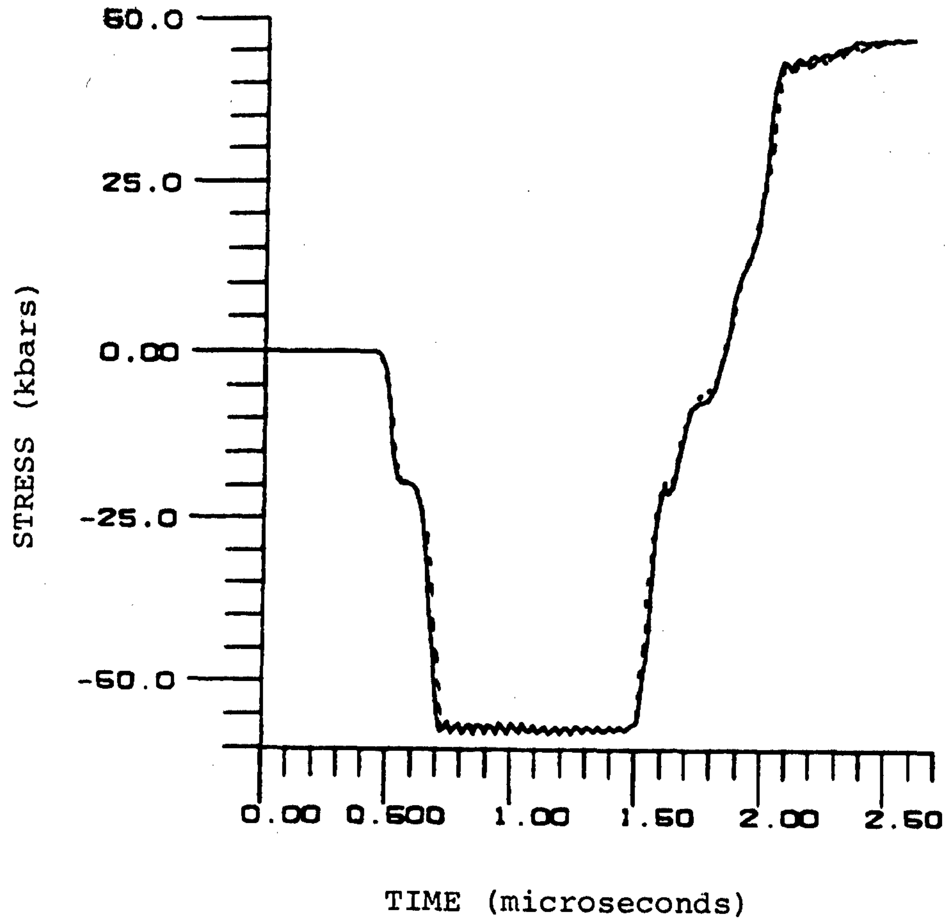

Figure 5. Comparison of Stress Histories at the Spall Plane for the Indirect Approach. [... STEALTH without B-P Model; —— STEALTH with B-P Model.]

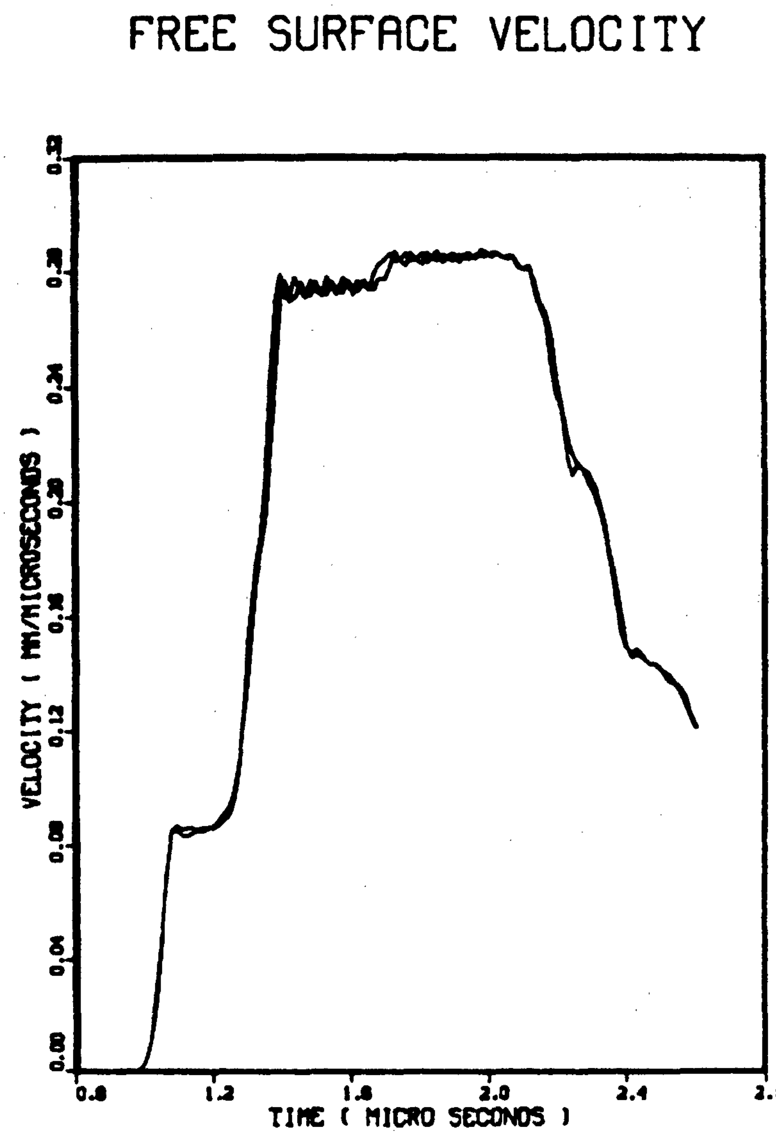

Figure 6. Comparison of Free Surface Velocity Histories for the Indirect Approach. (The plots from STEALTH with and without using B-P Model are almost identical.)

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APPENDIX A
STEALTH ADDITIONS

The Bodner-Partom plastic flow model has been successfully incorporated into the STEALTH 1D computer code. This task required new common block variables, additional input parameters, additions to twelve STEALTH routines, and six new subroutines.

A total of 62 new variables were added to four STEALTH common blocks (/MATARY/, /MATVAR/, /ZONARY/, and /ZONVAR/). The new variables in /MATARY/ and /MATVAR/ are used to store values for the input material-dependent Bodner-Partom parameters, while those in /ZONARY/ and /ZONVAR/ are used to store the additional zone variables used in the Bodner-Partom solution. Tables A-1 and A-2 describe these new common variables in more detail. Five of the new zone variables (PWK, EP1, PS1, TS1, and EFS) have been given identifier numbers so that they may be printed and/or plotted. However, the three new zone variables relating to plastic flow (PWK, EP1, and PS1) are only computed by the Bodner-Partom model, so printing or plotting these variables is meaningless during a "standard" STEALTH run without using the B-P model. Appendix B provides the identifier numbers for these new zone variables.

Five new input record types have been added to the material specification phase. Record type 116 is used to indicate the plastic flow model type (either standard STEALTH or STEALTH with the Bodner-Partom model), while record types 181, 182, 183, and 184 specify constants, constraints, and convergence parameters required by the Bodner-Partom plastic flow model. Omission of these new input records will result in a "standard" STEALTH run. However, if record type 116 is used to select the Bodner-Partom plastic flow model for a particular material, then record types 181, 182, and 183 <u>must</u> also be included for that same material. The convergence parameters on record type 184 have default values, so this record is always optional. Appendix C describes the new input record types.

Two initialization routines (CMNMAT and CMNZON) were changed in order to initialize all the new common block variables. INIPTR, another initialization routine, was modified so that five of the new zone variables (PWK, EP1, PS1, TS1, and EFS) could be printed and plotted. Code was added to three input routines (MATINP, MATCHK, and MATPRT) so that the Bodner-Partom parameters could be read in, checked, and printed out during the material specification phase. In addition, MATPRM was changed so that the values of the new variables in /MATVAR/ would always correspond to the current material. Code was added to subroutines ZONOLD and ZONNEW in order to retrieve old values and store new values for the new zone variables that were added to /ZONARY/. In subroutine ZONSDV, code was added to determine when the Bodner-Partom model should be used for plastic flow calculations. For plotting purposes only, subroutines ZONSTN and ZONSTR were modified to compute total xx strain and effective stress, respectively. Finally, six new subroutines were added to the STEALTH 1D code in order to compute the Bodner-Partom plastic flow solution: BODPAR, EPIJ, SDOTIJ, SIJDIF, SIJEST, and SIJNEW. Table A-3 summarizes the changes in each STEALTH routine, and Table A-4 briefly describes each new subroutine. Appendix D provides flowcharts for the new routines that were added to STEALTH.

TABLE A-1

MODIFIED STEALTH COMMON BLOCKS
FOR BODNER-PARTOM PLASTIC FLOW MODEL

Common Block	Additions
/MATARY/	Added 16 array variables: MAPLS(10), ADO(10), ASRN(10), AHRMO(10), AHRM1(10), AHRA(10), AZO(10), AZ1(10), ADEMAX(10), AEFSMN(10), AD2PMN(10), ATOLSD(10), ARLXSD(10), MAITSD(10), MACTSD(10), ATCFSD(10). See Table A-2 for variable definitions.
/MATVAR/	Added 16 variables: MPLS, DO, SRN, HRMO, HRM1, HRA, ZO, Z1, DEMAX, EFSMIN, D2PMIN, TOLRSD, RLAXSD, MITRSD, MCUTSD, TCFSD. See Table A-2 for variable definitions.
/ZONARY/	Added 8 array variables: PWK(202), EP1(202), PS1(202), TS1(202), EFS(202), SXXDT(202), SYYDT(202), SZZDT(202). See Table A-2 for variable definitions.
/ZONVAR/	Added 22 variables: PWKO, PWKN, EP1O, EP1N, PS1O, PS1N, TS1O, TS1N, EFSO, EFSN, SXXDTO, SXXDTN, SYYDTO, SYYDTN, SZZDTO, SZZDTN, SXYDTO, SXYDTN, SYZDTO, SYZDTN, SXZDTO, SXZDTN. See Table A-2 for variable definitions.

TABLE A-2

NEW COMMON VARIABLES IN STEALTH 1D

VARIABLE NAME	COMMON BLOCK ADDED TO	DESCRIPTION
MAPLS(L)	/MATARY/	Type of plastic flow model for material number L.
ADO(L)	"	Limiting value of strain rate for Bodner-Partom constants associated with material number L.
ASRN(L)	"	Strain rate exponent for material number L.
AHRMO(L)	"	Hardening rate parameter for material number L.
AHRM1(L)	"	Hardening rate parameter for material number L.
AHRA(L)	"	Hardening rate parameter for material number L.
AZO(L)	"	Initial value of hardness for material number L.
AZ1(L)	"	Maximum value of hardness for material number L.
ADEMAX(L)	"	Maximum allowable change in the total strain during one time step for material number L.
AEFSMN(L)	"	Minimum value of the effective stress for plastic flow in material number L.
AD2PMN(L)	"	Minimum value of the second invariant of the deviatoric plastic strain rate for plastic flow in material number L.
ATOLSD(L)	"	Relative convergence tolerance for the deviatoric stress computations for material number L.

ARLXSD(L)	/MATARY/	Relaxation factor used to accelerate the convergence of the deviatoric stresses for material number L.
MAITSD(L)	"	Maximum number of iterations allowed during computation of the deviatoric stresses for material number L.
MACTSD(L)	"	Maximum number of time step cuts allowed during computation of the deviatoric stresses for material number L.
ATCFSD(L)	"	Time step cut factor used to decrease the time step length when the deviatoric stresses fail to converge for material number L.
MPLS	/MATVAR/	Plastic flow model type.
DO	"	Limiting value of strain rate for Bodner-Partom constants.
SRN	"	Strain rate exponent.
HRMO	"	Hardening rate parameter.
HRM1	"	Hardening rate parameter.
HRA	"	Hardening rate parameter.
ZO	"	Initial value of hardness.
Z1	"	Maximum value of hardness.
DEMAX	"	Maximum allowable change in the total strain during one time step.
EFSMIN	"	Minimum value of the effective stress for plastic flow.
D2PMIN	"	Minimum value of the second invariant of the deviatoric plastic strain rate for plastic flow.
TOLRSD	"	Relative convergence tolerance for the deviatoric stress computations.

RLAXSD	/MATVAR/	Relaxation factor used to accelerate the convergence of the deviatoric stresses.
MITRSD	"	Maximum number of iterations allowed during computation of the deviatoric stresses.
MCUTSD	"	Maximum number of time step cuts allowed during computation of the deviatoric stresses.
TCFSD	"	Time step cut factor used to decrease the time step length when the deviatoric stresses fail to converge.
PWK(i)	/ZONARY/	Total plastic work done in zone number i.
EP1(i)	"	Plastic xx strain rate in zone number i.
PS1(i)	"	Plastic xx strain in zone number i.
TS1(i)	"	Total xx strain in zone number i.
EFS(i)	"	Effective stress in zone number i.
SXXDT(i)	"	Deviatoric xx normal stress gradient in zone number i.
SYYDT(i)	"	Deviatoric yy normal stress gradient in zone number i.
SZZDT(i)	"	Deviatoric zz normal stress gradient in zone number i.
PWKO	/ZONVAR/	Plastic work at old time.
PWKN	"	Plastic work at new time.
EP1O	"	Plastic xx strain rate at old time.
EP1N	"	Plastic xx strain rate at new time.
PS1O	"	Plastic xx strain at old time.
PS1N	"	Plastic xx strain at new time.

TS1O	/ZONVAR/	Total xx strain at old time.
TS1N	"	Total xx strain at new time.
EFSO	"	Effective stress at old time.
EFSN	"	Effective stress at new time.
SXXDTO	"	Deviatoric xx normal stress gradient at old time.
SXXDTN	"	Deviatoric xx normal stress gradient at new time.
SYYDTO	"	Deviatoric yy normal stress gradient at old time.
SYYDTN	"	Deviatoric yy normal stress gradient at new time.
SZZDTO	"	Deviatoric zz normal stress gradient at old time.
SZZDTN	"	Deviatoric zz normal stress gradient at new time.
SXYDTO	"	Deviatoric xy shear stress gradient at old time.
SXYDTN	"	Deviatoric xy shear stress gradient at new time.
SYZDTO	"	Deviatoric yz shear stress gradient at old time.
SYZDTN	"	Deviatoric yz shear stress gradient at new time.
SXZDTO	"	Deviatoric xz shear stress gradient at old time.
SXZDTN	"	Deviatoric xz shear stress gradient at new time.

TABLE A-3

ADDITIONS TO EXISTING STEALTH ROUTINES

Routine	Additions
CMNMAT	Added code to initialize the new variables that were added to common blocks /MATARY/ and /MATVAR/.
CMNZON	Added code to initialize the new variables that were added to common blocks /ZONARY/ and /ZONVAR/.
INIPTR	Added 5 new variable names (PWK, EP1, PS1, TS1, and EFS) to the NAMVAR array data statement (at locations 77, 78, 79, 80, and 90 in the array). Also added code to store addresses and data types of these variables (in IDPTR and IDATT arrays) so that they can be printed and/or plotted.
MATCHK	Added code to check Bodner-Partom plastic flow model input parameters (from record types 181, 182, 183, and 184) for consistency and validity.
MATINP	Added code to read 5 new types of MAT input records (116, 181, 182, 183, and 184). The 116 input record specifies the plastic flow model type, while the 4 other input records define the parameters required by the Bodner-Partom plastic flow model.
MATPRM	Added code to define the new variables that were added to common /MATVAR/. These variables contain the Bodner-Partom plastic flow model parameters for the current material.
MATPRT	Added code to echo the Bodner-Partom plastic flow model input parameters (when appropriate) for each material.
ZONNEW	Added code to store new values of the zone variables related to the Bodner-Partom plastic flow model. These values are stored in the new array variables that were added to common /ZONARY/.
ZONOLD	Added code to define old values of the zone variables related to the Bodner-Partom plastic flow model. These values are retrieved from the new array variables that were added to common /ZONARY/.
ZONSDV	Added code to compute deviatoric stress gradients for elastic flow and to call Bodner-Partom routines for plastic flow (when appropriate).
ZONSTN	Added code to compute new total xx strain.
ZONSTR	Added code to compute new effective stress.

TABLE A-4

NEW STEALTH ROUTINES
FOR BODNER-PARTOM PLASTIC FLOW MODEL

Routine	Description
BODPAR	Controls the Bodner-Partom plastic flow model computations. This routine divides the STEALTH time step into smaller steps to facilitate convergence of the Bodner-Partom calculations. Output from this routine consists of the deviatoric stresses and stress gradients, the plastic work done (so far), the plastic xx strain rate, and the plastic xx strain.
EPIJ	Uses the Bodner-Partom viscoplastic state variable theory to compute the plastic strain rates and the second invariant of the deviatoric plastic strain rate.
SDOTIJ	Computes the deviatoric stress gradients.
SIJDIF	Computes the maximum relative difference between estimated and computed values of the deviatoric stresses.
SIJEST	Computes initial estimates for the new deviatoric stresses.
SIJNEW	Computes the new deviatoric stresses.

APPENDIX B

STEALTH VARIABLE IDENTIFIERS (IDS)*

1 TIM	2 TIE	3 TDE	4 THE	5 TKE	6 TEG	7 TXM	8 TYM	9 TXK	10 TYK
11 XPN	12 XVL	13 XAC	14 YPN	15 YVL	16 YAC	17 ZPN	18 ZVL	19 ZAC	20 DST
21 GXK	22 GYK	23 GZK	24 XHF	25 YHF	26 ZHF	27	28	29 TZM	30 TZK
31 NOR	32 NBM	33 NBT	34 NBV	35 ACT	36 MPN	37 IND	38	39	40
41 DLL	42 RLV	43 COM	44 QDA	45 VSR	46 DNS	47 ZMS	48 TRV	49	50
51 ZIE	52 ZDE	53 ZHE	54 ZSE	55 ZKE	56	57	58	59	60
61 TMP	62 CON	63 SHC	64 PRH	65 AVS	66 SSP	67 BFS	68 IGN	69	70
71 TXX	72 TYY	73 TZZ	74 TXY	75 TYZ	76 TXZ	77 PWK	78 EP1	79 PS1	80 TS1
81 SXX	82 SYY	83 SZZ	84 SXY	85 SYZ	86 SZX	87 YLD	88 SHR	89	90 EFS
91 EX1	92 EX2	93 EX3	94 EX4	95 EX5	96 EX6	97	98	99	100

*The identifiers are index (address) values for the arrays IDPTR (variable pointer) and IDATT (variable attribute) found in subroutine INIPTR. Variables 1-10 are global variables, while the rest are either grid-point or zone-related. Variable definitions may be found in Appendix "Conventions" of Volume 3, "Programmer's Manual."

APPENDIX C

ADDITIONAL STEALTH INPUT RECORDS

PLASTIC FLOW MODEL TYPE

page 1 of 1

TYPE 116

The 116 input record specifies the type of plastic flow model for material MPN. If the 116 input record is omitted, the default value is used. The 116 input record may be used at restart time to change the plastic flow model type.

START	0	MAXMAT
RESTART	0	MAXMAT

Columns	11	21	31	41	51	61	71	80
	MPN	MPLS	---	---	---	---	---	
Fields	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MPN	Material property number. See Field Number 1 on TYPE 111 record.
2	MPLS	Plastic flow model type. The value for MPLS identifies the type of plastic flow model for material MPN. The value of MPLS must be integral and must be greater than or equal to 1 and less than or equal to 2. If MPLS is out of this range, a RGEERR message is written on the print and the message files and the program terminates immediately in subroutine MATINP. (See Appendix "Messages.") The following definitions apply: = 1.0 standard STEALTH (default) = 2.0 Bodner-Partom Parameters required by the Bodner-Partom model are entered on input records 181, 182, 183, and 184. There are no additional parameters associated with the standard STEALTH model.
3-7	---	Fields 3-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages.")

The 181 input record specifies the strain rate parameters (for material MPN) required by the Bodner-Partom plastic flow model. The 181 input record is absolutely required when the Bodner-Partom model is specified (MPLS=2 on the 116 input record); it is ignored when the standard STEALTH plastic flow model is specified (MPLS=1 on the 116 input record). The 181 record may be used at restart time to change the Bodner-Partom strain rate parameters.

START	0	MAXMAT
RESTART	0	MAXMAT

Columns	11	21	31	41	51	61	71	80
	MPN	DO	SRN	---	---	---	---	
Fields	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MPN	Material property number. See Field Number 1 on TYPE 111 record.
2	DO	Limiting value of strain rate. The value of DO must be greater than 0.0.
3	SRN	Strain rate exponent. The value of SRN must be greater than 0.0.
4-7	---	Fields 4-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages.")

The 182 input record specifies the material hardening parameters (for material MPN) required by the Bodner-Partom plastic flow model. The 182 input record is absolutely required when the Bodner-Partom model is specified (MPLS=2 on the 116 input record); it is ignored when the standard STEALTH plastic flow model is specified (MPLS=1 on the 116 input record). The 182 record may be used at restart time to change the Bodner-Partom material hardening parameters.

START	0	MAXMAT
RESTART	0	MAXMAT

Columns	11	21	31	41	51	61	71	80
	MPN	HRMO	HRM1	HRA	ZO	Z1	---	
Fields	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MPN	Material property number. See Field Number 1 on TYPE 111 record.
2	HRMO	Hardening rate parameter, m . The value of HRMO must be greater than 0.0.
3	HRM1	Hardening rate parameter, m . The value of HRM1 must be greater than or equal to 0.0.
4	HRA	Hardening rate parameter, α. The value of HRA must be greater than or equal to 0.0.
5	ZO	Initial value of hardness. The value of ZO must be greater than 0.0.
6	Z1	Maximum value of hardness. The value of Z1 must be greater than 0.0.
7	--	Field 7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages.")

The 183 input record specifies constraints (for material MPN) required by the Bodner-Partom plastic flow model. The 183 input record is absolutely required when the Bodner-Partom model is specified (MPLS=2 on the 116 input record); it is ignored when the standard STEALTH plastic flow model is specified (MPLS=1 on the 116 input record). The 183 record may be used at restart time to change the Bodner-Partom constraints.

START	0	MAXMAT
RESTART	0	MAXMAT

Columns	11	21	31	41	51	61	71	80
	MPN	DEMAX	EFSMIN	D2PMIN	---	---	---	
Fields	1	2	3	4	5	6	7	

Field Number	Input Variable Name	Description of Input Variable
1	MPN	Material property number. See Field Number 1 on TYPE 111 record.
2	DEMAX	Maximum allowable change in the total strain during one time step. The value of DEMAX must be greater than 0.0.
3	EFSMIN	Minimum value of the effective stress for plastic flow. The value of EFSMIN must be greater than 0.0.
4	D2PMIN	Minimum value of the second invariant of the deviatoric plastic strain rate for plastic flow. The value of D2PMIN must be greater than 0.0.
5-7	--	Fields 5-7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages.")

The 184 input record specifies convergence parameters (for material MPN) required by the Bodner-Partom plastic flow model. Default values are used if the 184 input record is omitted when the Bodner-Partom model is specified (MPLS=2 on the 116 input record). This record is ignored when the standard STEALTH plastic flow model is specified (MPLS=1 on the 116 input record). The 184 input record may be used at restart time to change the Bodner-Partom convergence parameters.

START	0	MAXMAT
RESTART	0	MAXMAT

Columns	11	21	31	41	51	61	71	80
	MPN	TOLRSD	RLAXSD	MITRSD	MCUTSD	TCFSD	---	
Fields	1	2	3	4	5	6	7	

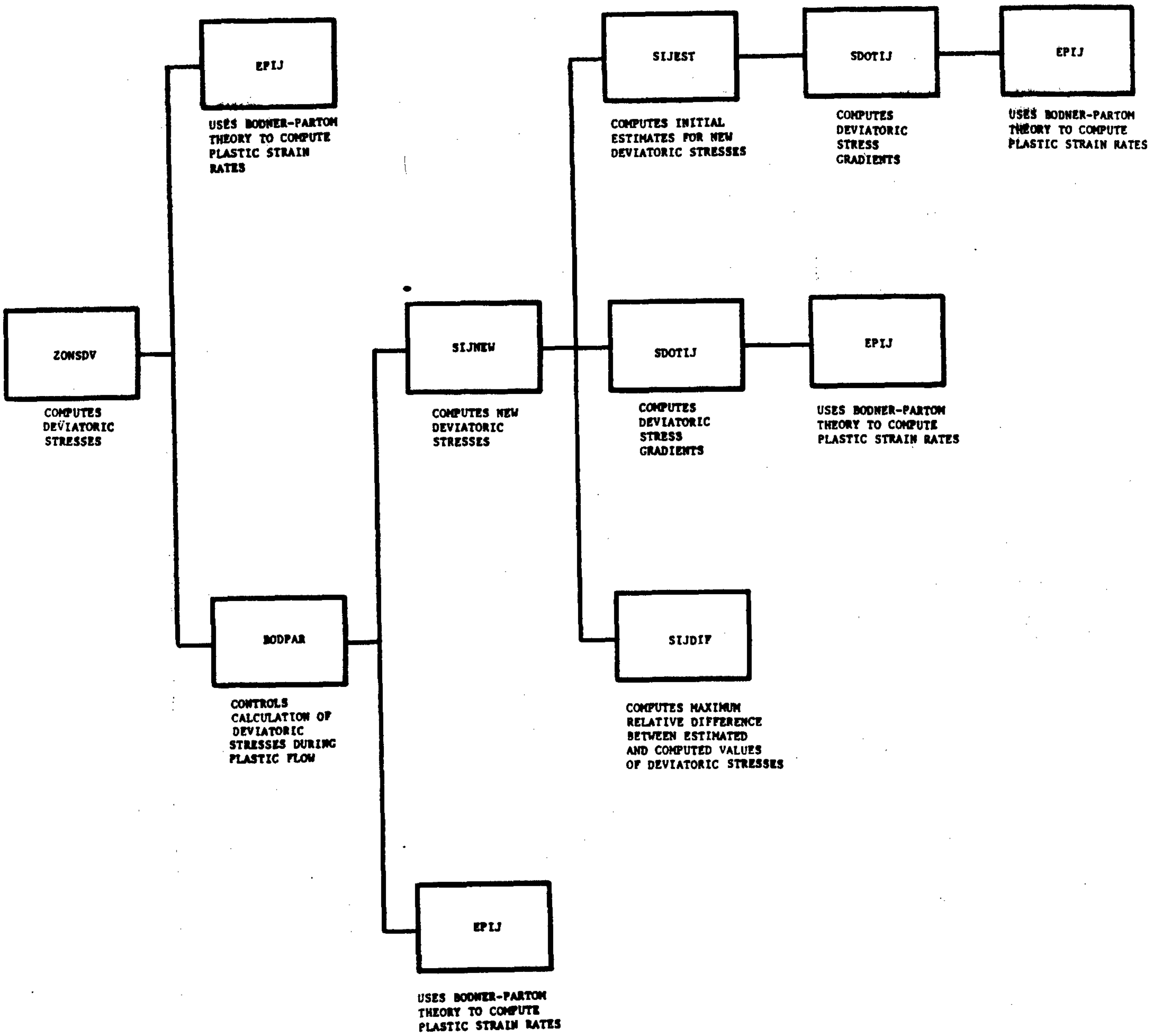
Field Number	Input Variable Name	Description of Input Variable
1	MPN	Material property number. See Field Number 1 on TYPE 111 record.
2	TOLRSD	Relative convergence tolerance for the deviatoric stresses. The value of TOLRSD must be greater than 0.0. If this field is left blank, the default value of 1.0×10^{-4} is assumed.
3	RLAXSD	Relaxation factor used to accelerate the convergence of the deviatoric stresses. The value of RLAXSD must be greater than 0.0 and less than or equal to 1.0. If this field is left blank, the default value of 1.0 is assumed.
4	MITRSD	Maximum number of iterations allowed during computation of the deviatoric stresses. The value of MITRSD must be integral and greater than or equal to 1. If this field is left blank, the default value of 5 is assumed.

Columns	11	21	31	41	51	61	71	80
	MPN	TOLRSD	RLAXSD	MITRSD	MCUTSD	TCFSD	---	
Fields	1	2	3	4	5	6	7	

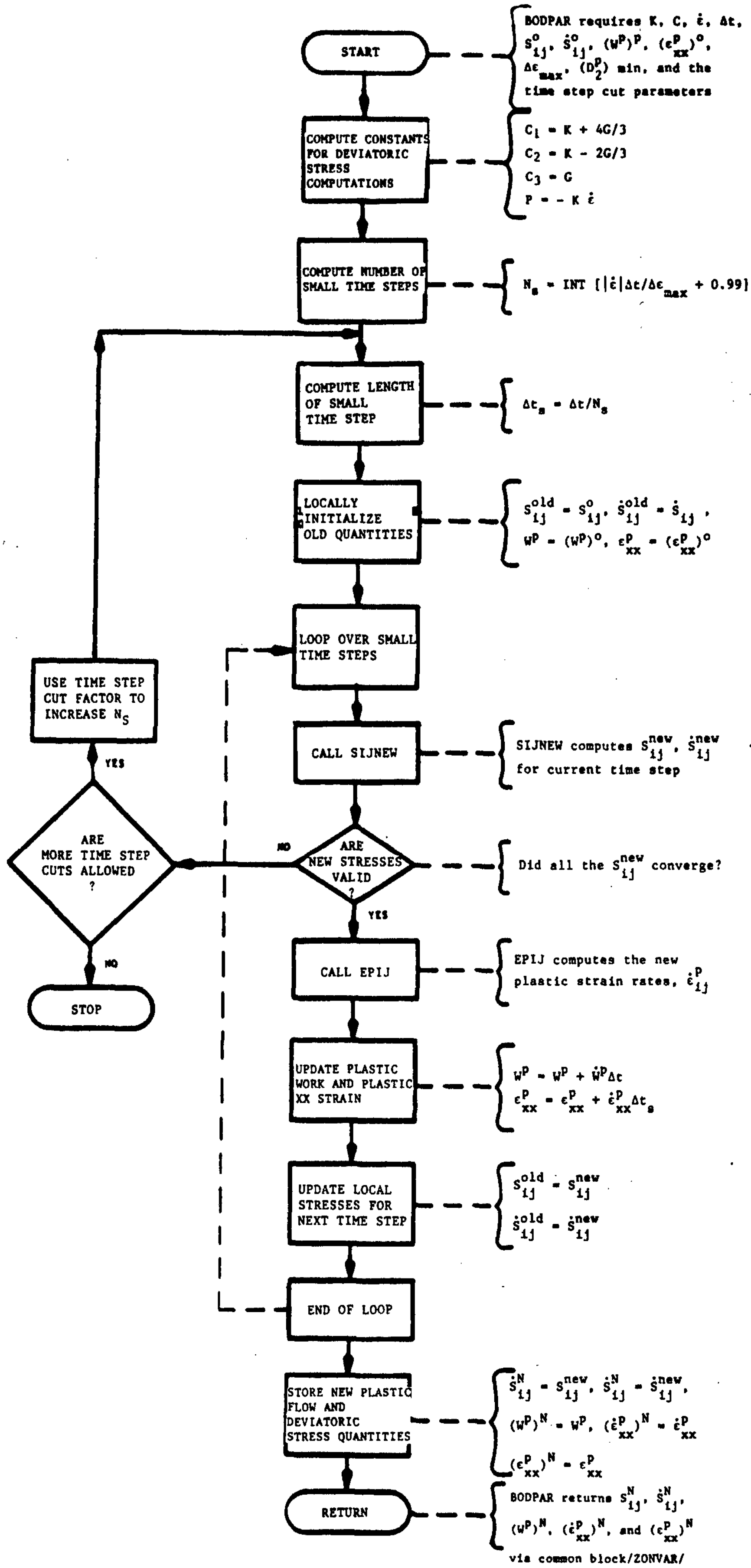
Field Number	Input Variable Name	Description of Input Variable
5	MCUTSD	Maximum number of time step cuts allowed during computation of the deviatoric stresses. The value of MCUTSD must be integral and greater than or equal to 1. If this field is left blank, the default value of 10 is assumed.
6	TCFSD	Time step cut factor used when the deviatoric stresses fail to converge. The value of TCFSD must be greater than 1.0. When a time step cut is made, the length of the new time step is equal to the old time step divided by TCFSD; i.e., TCFSD = 2.0 causes the time step length to be cut in half at each time step cut. If this field is left blank, the default value of 2.0 is assumed.
7	--	Field 7 must be left blank or the FLDCHK message is written on the print and the message files and the program terminates at the end of the GENERATOR phase group. (See Appendix "Messages.")

APPENDIX D

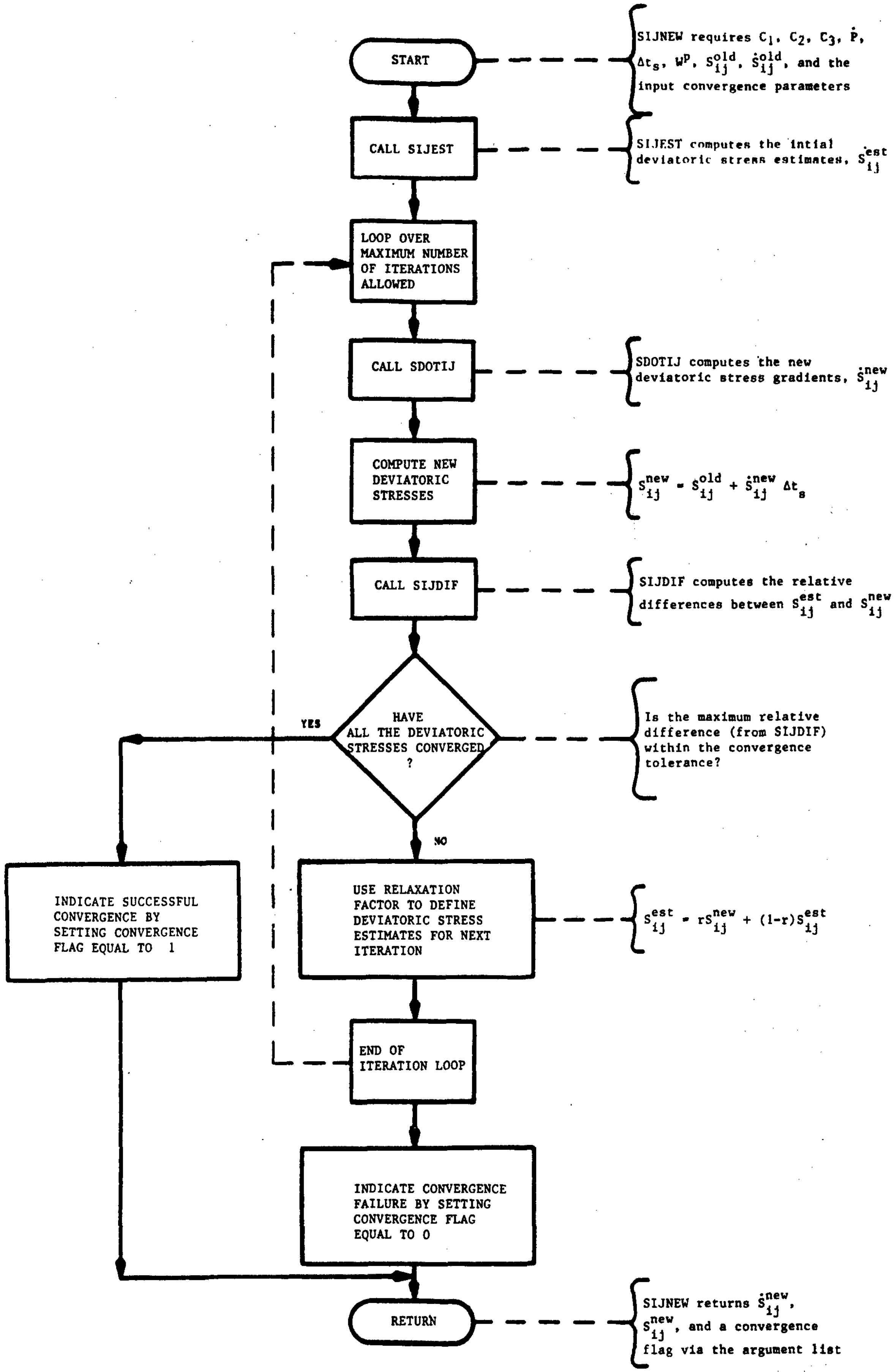
FLOWCHARTS ON NEW SUBROUTINES



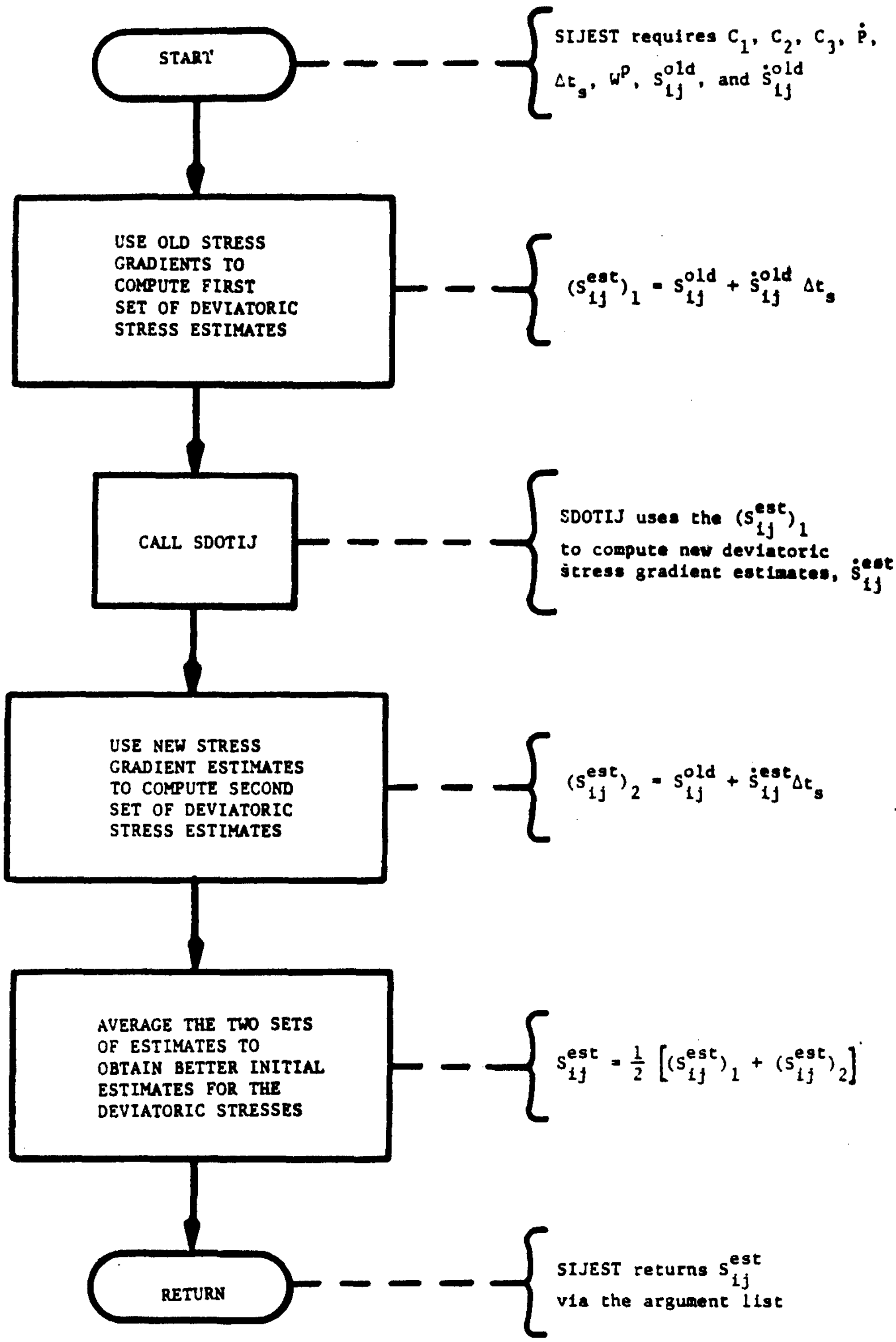
FLOW DIAGRAM FOR BODNER-PARTOM PLASTIC FLOW MODEL IN STEALTH 1D



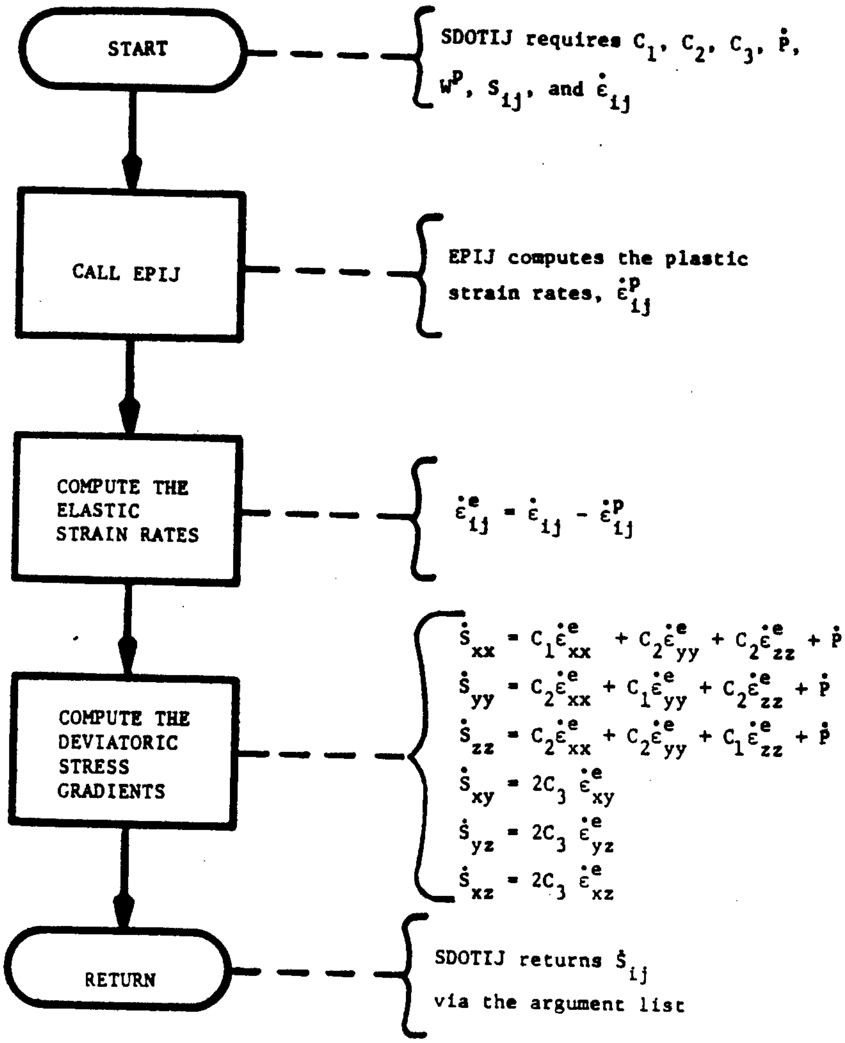
BODPAR Flowchart



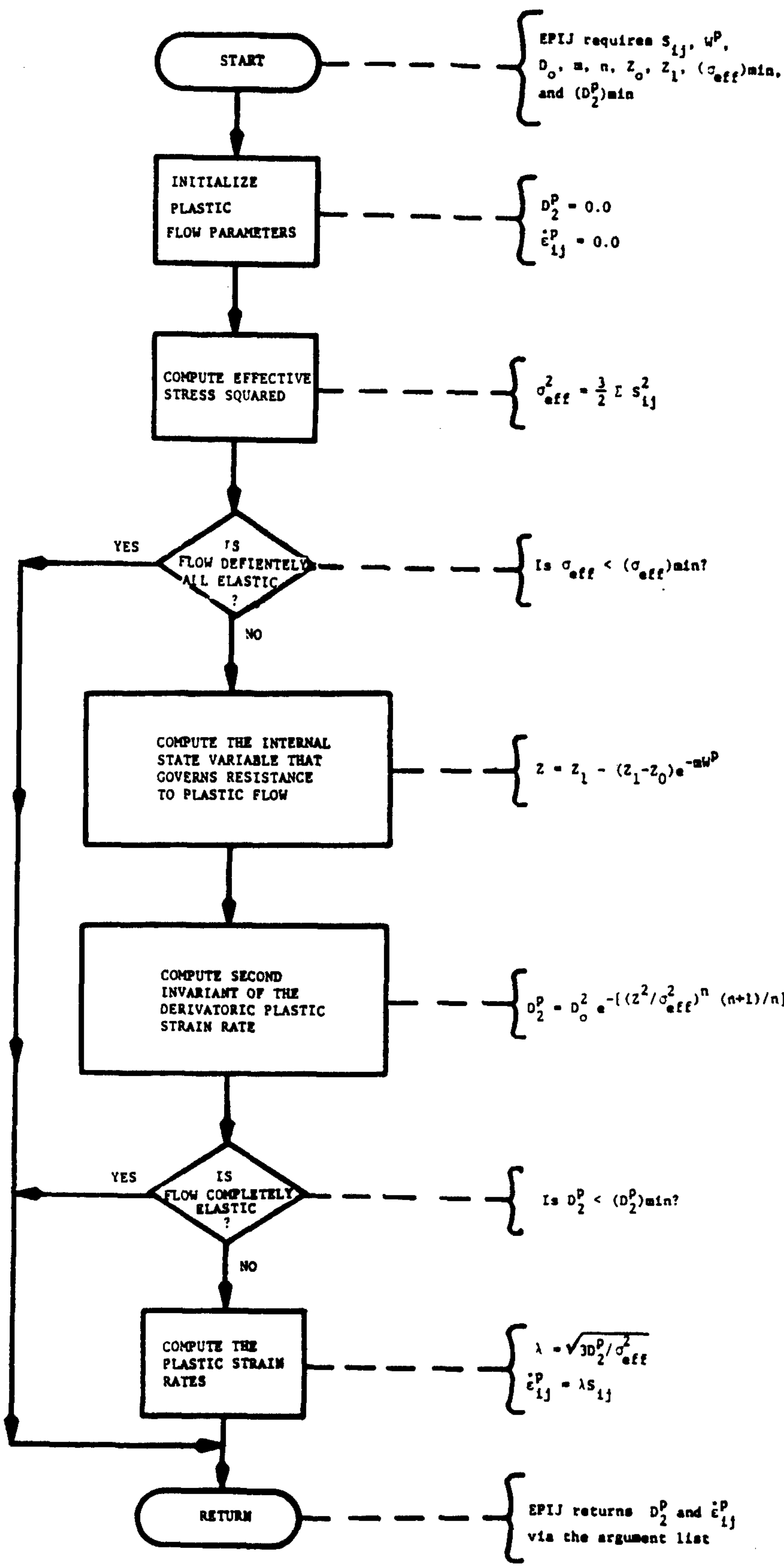
SIJNEW Flowchart



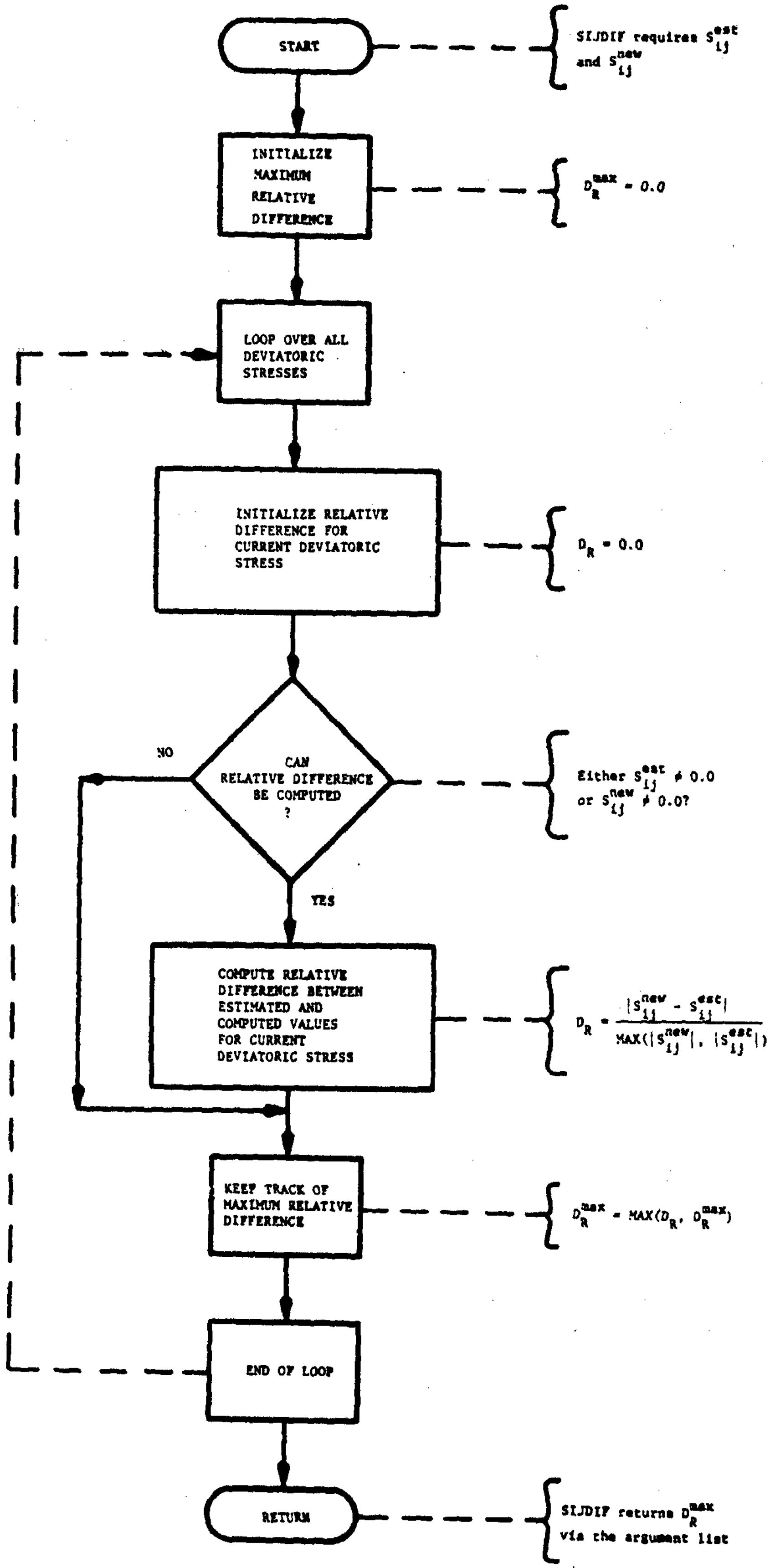
SIJEST Flowchart



SDOTIJ Flowchart



EPIJ Flowchart



SIJDIF Flowchart

APPENDIX E

INPUT DATA FOR STEALTH TO
ANALYZE A TENSILE BAR

```
TTL        1D THIN ROD, V=10 M/S, B-P, RATE INDEPENDENT.
PRB
SYM            6.0000
GRD            1.0000    0.0000   11.0000
END
MAT
111            1.0000    1.0000
112            1.0000    2.0000    2.0000
116 PLSMOD     1.0000    2.0000
121            1.0000    7.8560
122            1.0000    1.0000              1.5400
123            1.0000  -10.0000   10.0000 .33663366    154.00    1.0000
132            1.0000  999.0000
134            1.0000    0.7940
181 BPSTRN     1.0000  100.0000    6.5000
182 BPHARD     1.0000  200.0000    0.0000    0.0000    0.0150    0.0150
183 BPCNST     1.0000    1.0E-4    1.0E-5   1.0E-10
184 BPCONV     1.0000    1.0E-4    1.0000   10.0000   10.0000    2.0000
END
GPT
211            1.0000    1.0000
212            1.0000   -5.0000    0.5000    2.0000
212            2.0000   50.0000    0.5000    3.0000
221            1.0000    1.0000   11.0000
241            1.0000   10.0000    0.0000   10.0000
END
ZON
311            1.0000    1.0000   11.0000
321            1.0000    1.0000
322            1.0000    1.0000
END
BDY
421            1.0000    5.0000    5.0000
421           11.0000    4.0000    5.0000    1.0000
422            1.0000    1.0000
441            1.0000    1.0000    0.0000    1.0E+4
442            1.0000    0.0010    0.0000
END
TIM
511            0.0100
512            0.0050   10.0000
521           1000.00   1000.00
END
EDT
621 PRTEDT     1.0000   999.000   1000.00    1.0000
622 PRTPTS     1.0000   11.0000
623 PRTIDS    11.0000   12.0000   45.0000   71.0000   72.0000   64.0000   66.0000
671 PLTEDT     1.0000    0.0000  1000.000    1.0000
672 PLOT       1.0000    1.0000   71.0000   80.0000    6.0000
672            2.0000    1.0000   71.0000    1.0000    6.0000
672            3.0000    1.0000   80.0000    1.0000    6.0000
END
END
```

APPENDIX F

INPUT DATA FOR STEALTH TO
ANALYZE A PLATE IMPACT TEST

```
TTL        1-D PLATE IMPACT, RATE INDEPENDENT.  IMP VEL = 300 M/S.  3MM --> 6MM
PRB
MIN MINUM              1.0E-08                          1.0E-06
GRD FLYER   1.0000     1.0000    31.0000
GRD TARG    2.0000     1.0000    61.0000
END
MAT
111 EOS     1.0000     1.0000
112 STREN   1.0000     2.0000     2.0000     2.0000
116 PLSMOD  1.0000     2.0000
121 DENS    1.0000    78.5600
122 BULK    1.0000     1.0000             1540.0000
132 YIELD   1.0000   999.0000
134 SHEAR   1.0000   794.0000
136 SPALL   1.0000  -999.0000
181 BPSTRN  1.0000   100.0000     6.5000
182 BPHARD  1.0000     0.2000     0.0000     0.0000    15.0000    15.0000
183 BPCNST  1.0000     1.0E-4     1.0E-5     1.0E-10
184 BPCONV  1.0000     1.0E-4     1.0000    10.0000    10.0000     2.0000
END
GPT
211 IL,XL   1.0000     1.0000               -3.0000
211         2.0000    32.0000                0.0000
221 IL,IR   1.0000     1.0000    31.0000
221         2.0000    32.0000    92.0000
241 XL,XR   1.0000    30.0000    -3.0000     0.0000
241         2.0000    60.0000     0.0000     6.0000
END
ZON
311 IL,IR   1.0000     1.0000    31.0000
311         2.0000    32.0000    92.0000
321 MPN     1.0000     1.0000
321         2.0000     1.0000
322 RLV     1.0000     1.0000
322         2.0000     1.0000
331 XVL     1.0000     0.3000
END
BDY
421 LBCFLR  1.0000     3.0000     5.0000
421 RBCFLR 31.0000     7.0000     5.0000
421 LBCTRG 32.0000     7.0000     5.0000
421 RBCTRG 92.0000     3.0000     5.0000
END
TIM
511 TIMSTP  0.0020
512 STPLIM  0.0019    10.0000
513 STPFCT  1.2000     0.9000
521 TIMLIM  2.6000  1000.0000
END
EDT
671 PLTEDT  1.0000     0.0000     2.6000     0.0100
672 PLOT    1.0000     1.0000    12.0000     1.0000    92.0000
672         2.0000     1.0000    71.0000     1.0000    62.0000
END
END
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